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Review Article

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Overview of Closed–Loop Enhanced Geothermal Systems

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INFORMATION

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ABSTRACT

In recent years, the focus of energy industries shifted toward geothermal energy utilization due to environmental concerns. Numerous studies were conducted on Closed-loop and Open-loop Enhanced Geothermal Systems to analyze their feasibility, efficiency, and durability. As different studies focused on various aspects of the system, concerns regarding low heat transfer, circulation efficiency, wellbore instability, and economic viability were left unanswered. Additionally, simulators could not adequately capture the complexity of Enhanced Geothermal Systems (EGS). Another studied system, Advanced Geothermal Systems, has lower costs, better circulation, and no seismic consequences within the closed loop but still suffers from some issues encountered with EGS, such as heat transfer inefficiency. Moreover, geothermal system applicability is limited, especially in deep wells or wells with high thermal gradients. This paper summarizes some of the issues associated with EGS closed-loop systems based on previous studies.

1. Introduction

Fossil fuels are the primary energy resource of the world. In recent years, due to fore fronted environmental concerns and climate change warnings, there is an increasing trend among communities to revive alternative energy resources such as wind, solar and geothermal energy.

The most prominent resource that has the potential to utilize the technology developed in oil-field exploration and production is geothermal energy, and it is a promising candidate to decline fossil fuel dependency. This triggered the development of new geothermal systems, and the most marked application is EGS.

EGS systems can be implemented in two ways: open-loop and closed-loop (Dandelion Energy, 2020). Although closed-loop systems are relatively new and technically demanding, both implementations can harness the hot fluid produced from geothermal reservoirs. The closed loop systems are more complex due to creating a circulation between the injection well, production well, and the high-temperature reservoir. On the other hand, the open-loop, so-called pump-and-dump systems are based on utilizing underground water. The overall idea is that the fluid, generally water or steam, heated by a reservoir can be drained and sent to the surface energy plant facility to produce electricity. System selection criteria can be based on four main pros and cons listed below.

Comparison from different perspectives:

Cost: The open systems do not circulate any reused fluid, so it is still free of the charges of injecting fluid into the reservoir, which comes with a burying pipe operation and its maintenance for the continuity of the production.

Feasibility: A closed system is more feasible since it does not require an aquifer or a fresh water source near the system.
Durability: A closed system is more durable and can last decades once installed underground. An open loop does not offer the same durability because water quality or supply may diminish with time.

Environmental concerns: As expected, an open system poses an environmental concern as it relies on fresh water sources like aquifers. This is due to the possibility of contamination or environmental disturbance. On the other hand, closed systems do not have this concern much as they don't rely on an external fluid source and do not pump anything into the system after circulation.

Eastern Turkey owns a huge geothermal potential energy, and the Turkish Government benefits from this opportunity impressively. As a result of investments and incentives of the Turkish Government, Turkey is the fourth country in the world according to the total installed geothermal power generation capacity at year end 2022 (GeoEnergy, 2023).

Although Turkey utilizes geothermal energy effectively, the geothermal industry in Turkey seeks to improve the possible capacity in those regions. The reevaluation of proven geothermal reservoirs in Eastern Turkey is a trending topic in the industry (Ozdemir et al., 2021a; Ozdemir et al., 2021b). EGS may be a key method to get better production from those regions.

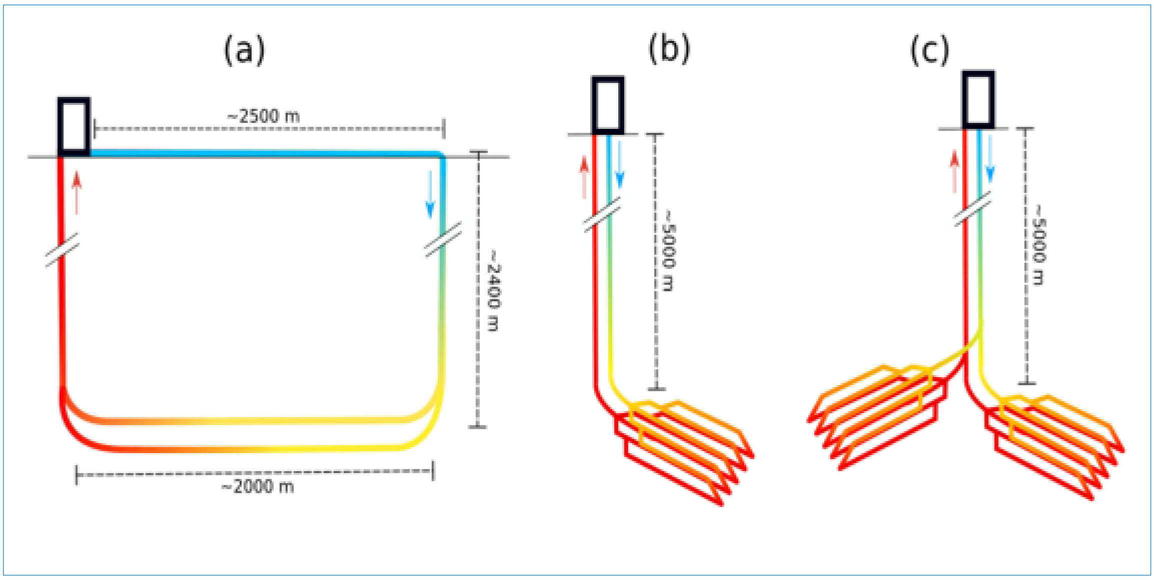

Fig. 1. EGS Close-Loop System (Illustration purpose only) (Kelly and McDermott, 2022)

2. Previous Studies

Various analyzes made by different researchers on closed-loop systems are available in the literature. Some of them are listed as follows

Falcone et al. (2018) evaluated conventional and unconventional deep geothermal well designs, focusing on the potential of using the Borehole Heat Exchanger (BHE) concept and heat conductive fillers to enhance heat exchange without direct fluid interaction with the surrounding formation. The goal of the evaluation was to identify more sustainable development options as an alternative to Enhanced Geothermal Systems (EGS) and to limit site-specific risks and avoid reservoir stimulation and induced seismicity.

Although the BHE concept was originally developed for shallow geothermal applications, it has the potential to be applied to greater depths, but only a few deep installations have been attempted so far with mixed results and not for the purpose of generating electrical power. Numerical simulations of a BHE design with heat conductive fillers were conducted and the results were encouraging, indicating the need for further research into engineered, closed-loop single-well solutions to tap into the potential of deep geothermal resources worldwide. These solutions could be initially applied in favorable locations such as shallower, high-temperature settings or where abandoned wells can be re-used to minimize operational costs.

Oldenburg et al. (2019) investigated the critical factors that control closed-loop geothermal energy recovery using a wellbore flow model called T2Well. The simulation results showed that permeability of the geothermal reservoir, injection temperature and flow rate of the working fluid, pipe diameter, and the choice of working fluid are important factors that affect the heat recovery process. It was found that water showed better heat extraction than CO_2 for certain flow rates, but CO_2 had higher pressure at the production wellhead which can aid in surface energy recovery.

The study concludes that there are complex interactions between the factors that will require advanced computational approaches to fully optimize. Using a detailed model, the researchers also found that the permeability of the reservoir is a primary control on energy gain by the working fluid, with natural convection strongly favoring heat transfer. They also found that flow rate and pipe diameter are important factors in the energy gain, and that a flow rate of 25 kg/s is the most that can be sustained in a 6-inch pipe. The passage suggests that further research is needed to optimize the use of CO_2 as a working fluid for closed-loop heat extraction.

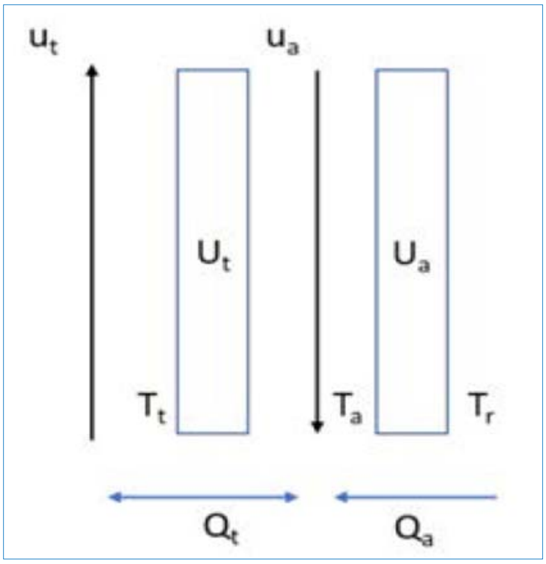

Fig. 2. Schematic of axial concentric flow (Livescu and Dindoruk, 2022b)

The research by Zhao (2013) describes a new semi-analytical modeling strategy for simulating natural fracture networks in heterogeneous tight formations. The new approach uses a "ghost fracture" concept and the source and sink function method to more accurately model the physics of natural fractures and can be applied to a wide range of complexities. The results from this new model are consistent with those from other commercial simulators but have higher accuracy and can handle more complex and irregular fractures. This new methodology can help in the development of tight oil and gas reserves by better understanding and analyzing the complex interactions among artificial and natural fractures and potentially assisting in identifying the best fractured formation ranges for drilling and fracturing.

Schulz (2008) conducted a study to understand the pressure drop behavior of sand-laden fracturing slurries in wellbores. Two different models were used for the study: a transparent model to observe fluid exchange and flow patterns visually and a high-pressure model to gather pressure drop data. The study found that the ratio of perforation diameter to average proppant size and the velocity of the fluid through the perforations have an impact on the tendency for sand to screen out at the perforations. Based on the laboratory data, a correlation was developed to predict the change of perforation coefficient due to proppant erosion. The study concludes that incorporating the change of perforation pressure drop during proppant stages in real-time bottom-hole treating pressure calculations will enhance the interpretation of treatment analysis.

This research provides insight on how to optimize the fluid and proppant selection to prevent sand bridging in perforation tunnels and to maintain a high fluid velocity to ensure proppant transport. Additionally, the study highlights the importance of understanding the pressure drop across the perforations during proppant stages, in order to improve the accuracy of the pressure calculations and optimize the treatment design.

Irani et al. (2022) conducted numerical studies on Hydraulic-Fractured Close-Loop systems. As a result of their studies, reaching the desired flow rate was impossible, which is one of the most critical problems in the operation of the Close-Loop system. Their study illustrates that many simulation studies are insufficient in modeling such complex systems and cannot cover the physics behind the whole process.

Kelly and McDermott (2022) suggested increasing the number of lateral wellbores. The problems associated with doing this include a reduction in efficiency due to thermal interference. Also, drilling a multi-lateral well is not a cost-effective approach, and its operational success is not easy to achieve. In conclusion of their study, the cost of building a closed-loop system is not profitable with the multi-lateral well drilling technique.

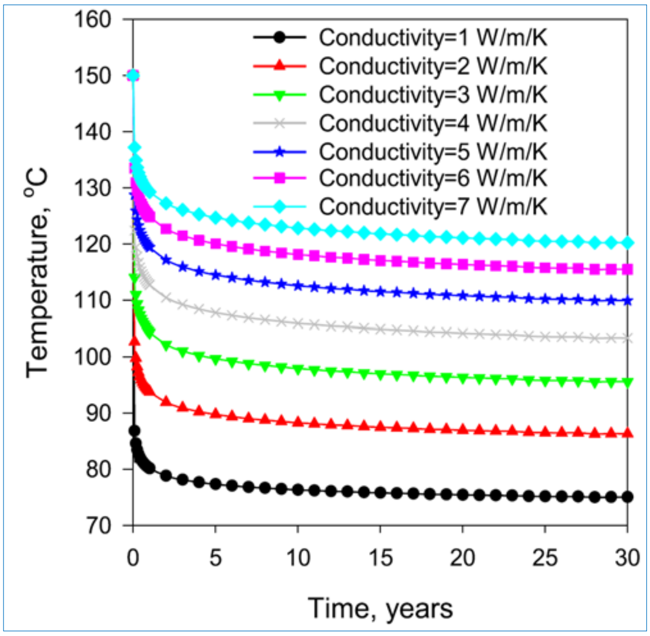

Fig. 3. Outlet temperature profile EGS Close-Loop System (Yuan et al., 2021)

Additionally, in terms of efficiency study, Sangfors (2021) reported that the circulation efficiency in the close-loop system is 13% when the input temperature is 150 °C, which is above the temperature of most abandoned oil and gas wells. For the reservoir modeling case, Higgings et al. (2021) emphasized that as a result of their analysis of the close-loop systems for the steam-dominated reservoirs, existing natural fractures were eliminated, and this should be further studied in the future. Furthermore, Melikyan and Egnatosyan (2012) emphasized that Close-Loop geothermal systems are effective for small building use. Studies on its feasibility for industrial purposes have not been conducted.

Several researchers quantitatively studied the process to answer the effectiveness of energy transfer. Sun et al. (2018) have made the following assumptions in their studies while using CO_2 as work fluid, which are:

- Only steady state flow is considered
- Reservoir heterogeneity neglected
- No mass loss in the systems

In the followed up paper (Sun et al., 2019), they suggested reducing the mass flow rate.

Wanju et al. (2021) emphasized that the heat loss in the vertical section can be compensated with multiple multi-lateral wells (Fig. 1). A lateral length of 1000s meters has been suggested without analyzing the feasibility. The assumption made in the study is that the earth is not affected by heat production. It has been stated that thermal conductivity is one of the driving parameters in these systems.

3. Discussion

Studies have been done on Closed-Loop EGS systems in many different configurations. As a result of these studies, the hydraulic fracturing method adapted from the petroleum sector has come to the forefront. This technology plays a significant role in both unconventional formations and geothermal reservoirs. In the latter application, the temperature and pressure are extremely high.

One of the well-known geothermal reservoirs is a hot-dry rock with no pore space, and the fracturing operation in such rocks is slightly different than the unconventional reservoir applications. In the former, hydrocarbons are produced from the same treatment well, while in the latter, heat is generated from hot-dry rocks by fluid flow through the fractures created be-tween injection and production wells. To illustrate this, experts drill two wells next to each other in a geothermal field. Then they frack both wells to provide a connection between wells. Later, water is injected from one well, and steam or hot water is produced from the other. Lastly, produced heat can be converted to electricity by geo-thermal power plants.

Livescu and Dindoruk (2022a; 2022b) mentioned Advanced Geothermal Systems (AGS) in their studies. Unlike the EGS, it aimed to carry the heat by circulating it in the well. The process provides fluid circulation by using the annulus between the tubing and casing.

Fig. 2 shows the axial concentric flow. With this proposed method, the interaction of the liquid with the rock in the reservoir is eliminated. Complications that may occur during the liquid-rock interaction are avoided. They thermally modeled the specified AGS system and showed that this system is more efficient than lateral wellbore configurations. AGS has several advantages over EGS.

- Fluid circulation pathway is better defined and controlled,
- Stimulation costs are eliminated.
- There are no possible seismic issues within the closed system.

The thermal conductivity of rocks is one of the most important factors limiting the performance of the closed-loop system (Livescu and Dindoruk, 2022a). The rock thermal conductivity value was evaluated as about 1 to 7 W/m/k (Fig. 3).

To increase long-term productivity, it is recommended to increase the lateral length, which will increase costs considerably. Thermal output fell rapidly within hours. Another study supporting this is carried out by Beckers et al. (2022).

The analysis of McClure (2021) depicts that the closed-loop system circulates fluid from a wellbore to the surface and relies on conduction while getting heat from the reservoir. However, conduction through solid rocks is a very slow process due to their low thermal diffusivity. Hence, this low efficiency and extremely low energy transfer impact the feasibility of the whole concept of a closed-loop geothermal system. Quantifying the potential energy can be roughly done with the equation of infinite-acting radial flow.

$$\Delta P = \frac{Q\mu}{4\pi kh}\left(ln\left(\frac{kt}{\mu \O c_t {r_w}^2}\right) + 0.80907\right) \qquad 1$$

The equation above can be modified by replacing pressure with temperature, porosity times compressibility with density times heat capacity and permeability divided by viscosity with thermal conductivity to get an equation for the heat production rate:

$$Q_t = \frac{4\pi Kh\Delta T}{ln\left(\frac{Kt}{\rho C {r_w}^2}\right) + 0.80907} \qquad 2$$

An example calculation with best case scenario is shown below:

Table 1. Best Case Scenario (Livescu and Dindoruk, 2022b)

Parameter	Value
Lateral Length	7,000 m
Thermal Conductivity	3 W/(K-m)
Wellbore Radius	10 cm
Heat Capacity	2,000 J/(kg-K)
Density	2,650 kg/m^3
Temperature Change	15 °C

$$Q_t = \frac{4 * \pi * 3 * 7{,}000 * 15}{\ln\left(\frac{3 * 365 * 24 * 3{,}600}{2{,}650 * 2{,}000 * 0.1^2}\right) + 0.80907} = 0.48\ MWth \qquad 3$$

With a 15% efficiency, this will be reduced to 0.072 MWe. The revenue from this could be calculated as:

$$0.072 * 1{,}000 * 0.15 * 24 * 365 = \$95{,}000 \qquad 4$$

Even with such an optimistic case, the revenue will not cover the millions of dollars involved in drilling and installing a closed loop geothermal. With that in mind, employing EGS would be a better alternative.

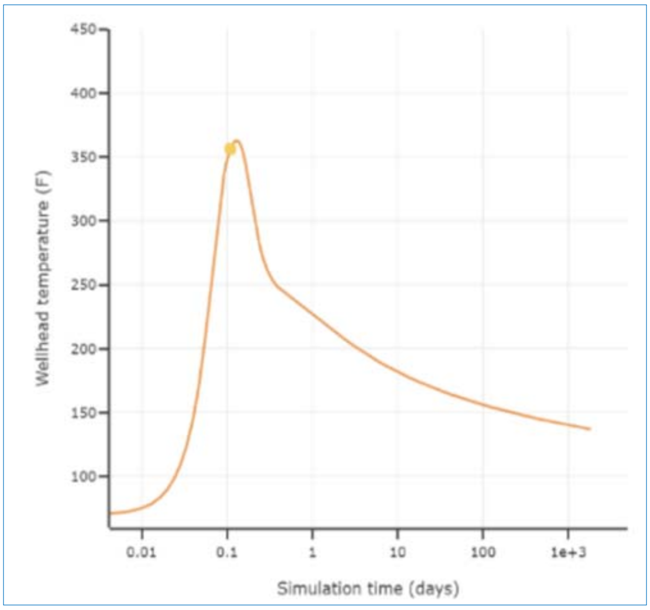

Fig. 4. ResFrac example case (McClure, 2021)

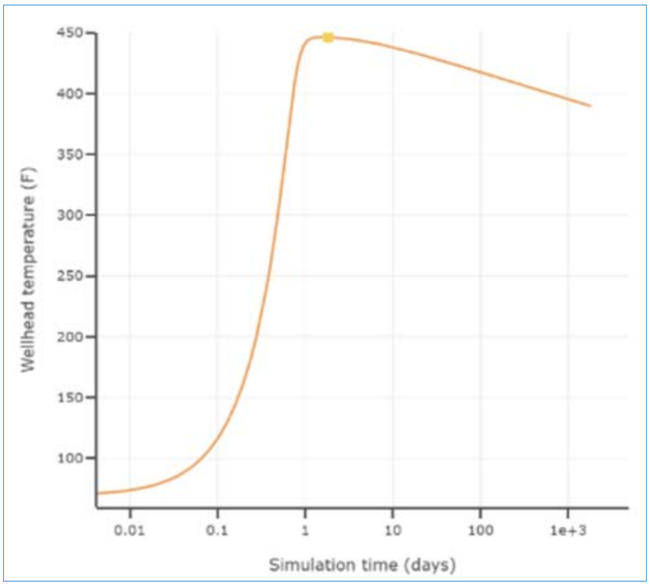

Fig. 5. Modified scenario results (McClure, 2021)

An example ResFrac Simulation was conducted to a further study closed loop Geothermal. The system studied is a U-Shaped with 3 segments each sized around 7 km. The system circulates 25,000 bbls/day and bottom-hole temperature is 450 °F. The temperature results show that production temperature maximum was around 360 °F and quickly drops to around 200 °F within days which is not enough for electricity generation (Fig. 4).

Modifying the scenario by adding insulation and decreasing the flowrate to 2,000 bbl/day generates the following results in Fig. 5.

Although maximum temperature increased to 450 °F, the water extraction rate is too low to cover the initial project costs. Hence, this again stresses the economical limitation of closed loop geothermal systems.

Another crucial point here is that pressure losses through the pipe will harm financial benefits and operational safety. In many studies, these pressure losses were omitted.

To give a simple example for this, assume we have 10,000 ft of 5 ½ pipe (P-110 class, ID: 4.778 in) with a weight of 20 lb per foot. The well is vertical and circulation of fresh water ($\varepsilon/D=0$). If you pump 500 bpm (roughly 1 m^3/sec), the total pipe friction pressure is calculated below;

$$N_{Re} = \frac{1.592 * 10^4 * (500\,bpm) * (8.33\,ppg)}{(4.778\,in) * (1\,cp)} = 13{,}877{,}520 \qquad 5$$

Reynolds number is greater than 4,000, which basically tells us it is turbulent flow.

$$f(D) = [\frac{1}{-1.8 * log_{10}[(\frac{0}{3.77})^{1.11} + (\frac{6.9}{13{,}877{,}520})]}]^2 = 0.007767 \qquad 6$$

Fanning Friction Factor is;

$$\frac{f(D)}{4} = \frac{0.007767}{4} = 0.0019419 \qquad 7$$

Pipe Friction Pressure;

$$\frac{11.41 * 0.0019419 * (10{,}000\,ft) * (8.33\,ppg) * (100\,bpm)^2}{4.778^5} = 7{,}401\,psi \qquad 8$$

Without running friction reducer during the circulation, there will be 7,401 psi of frictional losses.

4. Conclusion

EGS systems have been designed in many different configurations. The working mechanism and efficiency of each may differ operationally. At the moment, there is no tested design or field application. The weak points that need to be improved in this regard are listed as follows.

- It has been reported that the heat transfer rate of the rocks is low (McClure, 2021).
- Instability in wellbores planned to produce hot fluid for 20 to 40 years seems to be the main issue in EGS projects (McGregor et al., 2021).
- In the AGS method, there are not enough studies yet on the 20 to 40-year effect of the cold water pressed through the tubing and the hot water planned to be taken from the tubing-casing annulus.
- 80% of the water injected in the wells with cracked gaps is lost by the thief fracture, reducing the production considerably.

- The overall system efficiency has been reported as 13-15% in some cases (Melikyan and Egnatosyan, 2012; Sun et al., 2018; Sun et al., 2019; McClure, 2021; Yuan et al., 2021; Livescu and Dindoruk, 2022a; Livescu and Dindoruk, 2022a; Beckers et al., 2022).
- In EGS design, closures will occur in hydraulically cracked cracks as cold water circulates from the hot wellbore.
- The bottom-hole temperatures of abandoned oil and natural gas wells proposed to be used in geothermal applications to reduce investment costs are generally below 150 °C (McGregor et al., 2021).
- The digestibility of the assumptions made is a matter of debate.
- In general, the pressure losses that will occur in the system have not been mentioned much. For quantitative purposes, an example of the pressure loss calculation can be studied.
- Simulators cannot capture the complex physics behind the EGS system (Irani et al., 2022).
- When dealing with a high-temperature gradient, the produced electricity decreases significantly (Akdas, 2020).

Statements and Declarations

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